TARDEC's Power and Energy Vision

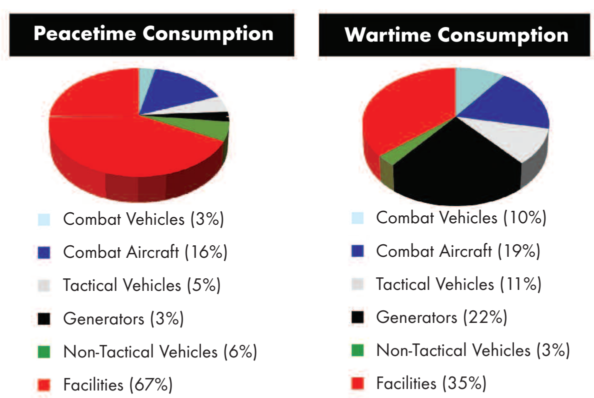
Prepared by the US Army Tank Automotive Research, Development and Engineering Center
US Army Research, Development and Engineering Command
Detroit Arsenal, Warren, MI

The Army is confronting power and energy challenges from national security issues related to foreign oil consumption, [including] the monetary and human costs of oil for DoD operations and climate change, with innovation in technology and the evolution of the current DoD fleet to more efficient combat systems. Driven by these challenges, TARDEC is taking on initiatives to lead the Army on fuel and energy with advancements in fuel efficiency, power management and an examination of how significant changes can be made from a life-cycle perspective.

– Dr. Grace M. Bochenek, TARDEC Director

The military's power and energy demands are growing rapidly. Consider the alternator in the High Mobility Multi-purpose Wheeled Vehicle (HMMWV). The current output increased from 85 amps to 400 to 600 amps in just two years. As the Department of Defense's (DoD) ground vehicle integration center, the power and energy vision of the US Army Tank Automotive Research, Development and Engineering Center (TARDEC) is focused on how energy sources can be connected on a flexible network to all combat systems. Energy is being studied from a layered structure perspective as four entities: generation, distribution, transfer and vehicle.

From TARDEC's perspective, vehicle power and energy are considered in terms of primary and non-primary power, energy storage, and power and thermal management. TARDEC has been exploring several options for power and energy for ten years. Some of these are highlighted in this article.



Peacetime and wartime fuel consumption.[1]

ENERGY STORAGE AND BATTERY TECHNOLOGY

As electric power-consuming systems proliferate in modern combat operations, there is a corresponding and critical need for electrical energy storage capacity. TARDEC has created programs to develop battery technologies, ranging from safer, more effective cathode chemistries to expanding domestic manufacturing capability in partnerships with private industry, so that both can reap the benefits of safer and more cost-effective technologies. These programs include work on new cathode materials for Lithium-ion (Li-ion) cells, nanocomposite cathode materials for high power needs, and an initiative to build the first US-automated manufacturing facility for Li-ion batteries to be used in the Future Combat Systems (Brigade Combat Team) (FCS (BCT)) Hybrid Electric (HE) fleet.

High-power, high-energy density, Li-ion batteries are being designed for use in Hybrid Electric Vehicle (HEV) propulsion systems. In addition, these batteries are being considered for other critical applications including auxiliary power units (APUs), plug-in hybrids, silent watch energy storage, pulse power delivery applications and future hybridized power source design.

In July 2004, TARDEC awarded a Manufacturing Technology (ManTech) Objective program contract that seeks to improve overall battery performance, safety, and reliability and reduce the manufacturing cost of Li-ion batteries by automating the battery manufacturing process and reducing production costs. Prior to this contract, there was no industrial base for these batteries; they were fabricated to customer order and therefore, quite expensive.

The contract scope includes 1,000 process improvement tasks taking place over a six-year performance period. Among the many tasks, these objectives will be addressed: manufacture of improved electrodes, cell closure and bussing/circuit breaker, and cell filling; cell formation; battery assembly; performance and safety assessments; and development of liquid cooled modules and prismatic cells. Currently, the tasks are broken up in to five generic categories: mixing, coating and winding; electrolyte filling; circuit breaker bussing and closing; electrical formation; and battery assembly. All these major tasks have separate individual sub-tasks that are being worked in parallel. Concurrently, TARDEC researchers are also working on cell safety and performance improvement.

Target metrics for the program include reducing the cost of the 30-kilowatt-hour battery pack by 50% while significantly increasing the battery power and energy density. Technology improvements will be integrated into the ManTech effort to include new electrolyte and electrode materials enhancing high-temperature

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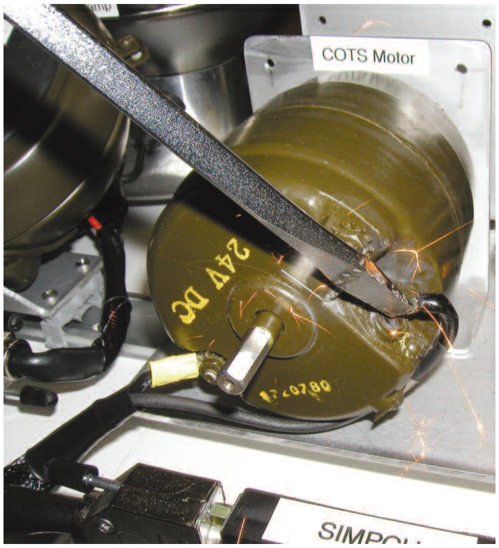

A short-circuit protection device used to protect equipment when military vehicles increasingly exceed the electrical power generation capability available for mission-critical equipment. (US Army TARDEC photo)

stability. Inherent within the cell structure, new circuit breaker technology that reduces the risk of overcharging and venting will also be integrated into the battery.

Another ManTech-related project the Army Research Lab is working in partnership with TARDEC is the development of a fire-retardant electrolyte and thin electrode materials to increase cell power density. One recent program achievement is the VL34P cell, an upgrade from the VL30P cell, that offers a higher-powered, higher-density cell with improved performance in several areas: a 14% improvement in energy density, an 11% improvement in weight, a 75% improvement in power density and a 63% decrease in cell labor hours.

All tasks are on schedule and proceeding according to plan. Also, processing adjustments are being made to accelerate key areas, such as battery assembly tasks, while equipment is being purchased and installed and process trials are being conducted. In addition, the Li-ion automated manufacturing facility is being reconfigured and streamlined in accordance with Lean Six Sigma principles to decrease labor hours, automate processes and reduce costs.

Eventual benefits of these innovative production processes and products will be affordable, high-power and high-energy density Li-ion batteries suitable for traction and pulsed power applications. Pulsed power applications, such as lasers, could use Li-ion batteries as a power source to provide direct support for directed-energy weapons.

It is noteworthy that as the process improvements are being brought on-line, improved and lower cost cells are already being produced for other related military applications. This exemplifies the effect of leveraging the ManTech investment well beyond the originally defined program objectives.

At the beginning of the program, there was no automated manufacturing plant for Li-ion batteries in the US. Since then there has been significant progress in the development of the technology. The power and energy density of Li-ion batteries has been improved and the manufacturing process has been fully automated with built-in quality control procedures inherent to the production line. In addition, affordable, high-power and high-energy density battery packs for HEV dash mobility, silent watch capabilities, pulse power for electric weapons, and increased survivability are now available.

HYDROGEN AS AN ALTERNATIVE FUEL

TARDEC is a part of the hydrogen refueling cooperative program that is providing important data to the US Army and the Department of Energy (DOE) to help determine the best alternatives to fossil fuels. A hydrogen fueling station (HFS) was opened at Selfridge Air National Guard Base (SANGB), MI, and is providing valuable real-world operational data for the DOE's Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Program. This station will provide insights into the economical and technical viability of using hydrogen as a transportation fuel.

The HFS houses a piece of equipment known as a "reformer" that converts natural gas into hydrogen. The hydrogen is compressed to greater than 5000 psi and stored in gaseous tubes. The hydrogen is then dispensed through a mechanism that looks very similar to a regular gas pump. The dispenser has a nozzle and a communications cable that interacts with the Fuel Cell Vehicle (FCV) to get important refueling information, such as pressure and temperature. With that information, the dispenser calculates how full the hydrogen car's tank is and how much pressure must be applied to dispense the hydrogen into the vehicle.

An FCV looks similar to any other car, but it differs from a conventional vehicle in two primary ways. First, its exhaust is water that is potable with few to no contaminants. Second, if the FCV has been turned off for awhile, it will take a moment to charge before it can accelerate. Once driving down the road, the only indication that it is not a conventional car is the lack of

A US Marine Corps (USMC) Cougar-H MRAP vehicle stages a roadblock in the desert southwest of Lake Habbaniyah, Iraq. Traditional electrical generation methods, such as the standard engine-driven alternator, have practical limitations in output capacity that develop from the underlying physics, such as the ability to adequately cool the device in an engine compartment's harsh operating conditions and the desert climate found in Iraq. (USMC photo by SGT Jeremy M. Giacomino)

engine noise. Since relatively new technologies are being used, a comprehensive safety system is in place to continuously monitor equipment for temperature, pressure and possible leaks.

The HFS and FCVs are the result of two Cooperative Research and Development Agreements (CRADAs). Chevron entered into a CRADA with TARDEC's National Automotive Center (NAC) in 2005, which was followed by a CRADA with Hyundai Kia Motors in 2006. TARDEC also entered into an inter-agency

A Stryker is driven robotically through the Fort Gordon, GA, range during testing. Increased power demand on vehicles creates excessive heat, which can shorten component life and increase the burden on vehicle crews when cabin temperatures rise uncomfortably, placing further electrical demands on the system for cooling. (US Army photo by Larry Edmond)

agreement with SANGB to serve as the site for hydrogen fuel cell car testing and fueling station cold weather testing.

The SANGB facility has been a valuable part of the hydrogen FCV development and testing process because it is one of a few locations capable of providing cold weather data for FCVs and hydrogen fueling infrastructure. This project has been, and continues to be, an example of a successful public-private partnership.

According to the *Energy Independence and Security Act of 2007*, section 246, "Not later than January 1, 2010, the head of each federal agency shall install at least one renewable fuel pump at each federal fleet fueling center in the United States under the jurisdiction of the head of the Federal agency." As a result of the CRADAs between TARDEC, Chevron and Hyundai, TARDEC is at the forefront of upholding the US Army's 25-year plan to eliminate energy waste in facilities and reduce dependence on fossil fuels on its installations.

POWER MANAGEMENT

Military vehicles increasingly rely on a suite of mission-critical electronic Command, Control, Communications, Computer, Intelligence, Surveillance and Reconnaissance equipment that, collectively, places an increased load on the electrical system, exceeding available electrical power generation capability for a variety of mission operational requirements. Traditional electri-

M-240B machine gun mounted on a HMMWV. In such vehicles, particularly in a desert climate, increasing power demand creates excessive heat, resulting in the need for efficient power management. (US Army photo by Christopher Barnhart)

cal generation methods, such as the standard engine-driven alternator, have practical limitations in output capacity that develop from the underlying physics, such as the ability to adequately cool the device in an engine compartment's harsh operating conditions. Additionally, current initiatives to electrify vehicle subsystems promise to save fuel and extend missions but further burden electrical systems already at capacity.

To address the need for additional electrical power, two fundamental approaches exist: use the available power more efficiently, and permit the safe incorporation of additional power sources when mission needs dictate. *Power management*, a concept that includes the hardware, software and algorithms to more intelligently control electrical power generation and usage, addresses both approaches. It is, therefore, a systems engineering approach to the efficient use of electrical power on vehicle platforms and is also an important area of research, development and engineering for current and future military vehicles.

Power management is an integral component in developing our future vehicle fleet and furthering Army transformation in the area of ground vehicle technology. As a result, the TARDEC Power and Energy Integrated Product Team has identified power management as a critical technology area. Power management meets and/or enables many current and future military vehicle requirements including:

- Power System Situational Awareness (Information)
- Power Management
- Mode-Based Load Control & Scheduling
- Load Prioritization / Reduction / Shedding / Reconstitution Maintenance Improvements
- Signature Management
- Power Optimization
- Control and Optimization of Subsystems/Power Control Units (PCUs)
- Integrated Power and Thermal Management
- Condition-Based Maintenance Notifications
- Power Imbalance
- Degrading Loads
- Problems with Power Generation or Energy Storage Devices
- Automated Maintenance Operations and Diagnostics
- Power Integration – Controlled Contribution from Various Sources
- Charge Control – Ultracapacitor and Battery Charge Control Solution
- Safety & Survivability
- Planning & Training Related to Power and Energy
- System Integration and Conformance to TARDEC Power Management Application Programming Interface (PMAPI)
- After-Action Reporting
- Interconnectivity and Interoperability

Power management research has produced prototype hardware,

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software and algorithms. The primary hardware components (termed PCUs) are "smart switches" (or solid state relays) that are controlled through an embedded microprocessor. This microprocessor enables the switch to be programmed with default settings, such as the maximum current and voltages permitted, and to automatically turn off when these limits are exceeded. This smart switch protects vital equipment and the crew and permits disabling of only the equipment in danger, not the entire circuit branch. This increases the vehicle systems' operational readiness.

Communication with the PCUs is carried out through a lightweight, adaptive control network, such as a controller-area network, which is commonly used in vehicle systems. The PCUs can respond to out-of-range conditions even when communication with the central control computer has been disrupted, giving the system added robustness and capability.

The ability to communicate and control remote loads from a central computer provides an opportunity to optimize electrical power usage system-wide. Algorithms to balance power draw from multiple sources, including batteries, alternators, ultracapacitors and fuel cells, have produced overall system efficiency improvements in the range of 20% in simulations. On-vehicle implementations are planned on the Mine Resistant Ambush Protected (MRAP) RG-31 vehicle to prove the simulation results, and they are part of the Power and Thermal Management Technologies Army Technology Objective (ATO).

Given the rapid pace of technological improvements, there is a need to standardize component behavior to prevent hardware and software obsolescence. The key is to standardize functionality while allowing for variation in the actual implementation. As technology progresses, any compliant hardware and software should be easily incorporated into existing vehicle platforms. The standards-based approach is termed a PMAPI. The standard specifies the software functions, inputs and outputs, which the hardware must support. The initial PMAPI has been adopted by Program Manager FCS (BCT).

Two Small Business Innovative Research (SBIR) programs related to power management, Advanced Electrical Power Architecture (AEPA) and Advanced Electrical Thermal Management (AETM), involved producing prototype PCU and control and optimization software to control challenging vehicle electrical loads. Of particular note, the AEPA program produced a prototype power management system that was demonstrated at the Power and Energy Symposium and at TARDEC's booth at the Society of Automotive Engineers World Congress Conference in 2008. The AETM resulted in a prototype system using ultracapacitors, PCUs and control software designed to promote advanced cold start systems. It demonstrated optimization of the power available to a vehicle starter (simulated through load banks located in a cold chamber) through a combination of ultracapacitors and batteries, showing how power management can be applied to a technically challenging situation. The SBIR company is currently engaged in applying power management to one MRAP RG-31 vehicle and one Family of Medium Tactical Vehicles variant.

An AH-64D Apache Longbow helicopter flies a mission to support troops on the ground. TARDEC has embraced the international effort for R&D of non-petroleum-derived kerosene (synthetic jet fuel) through its efforts under the *AFI*, which could benefit helicopters such as the Apache Longbow. (Photo by Air Force TSGT Andy Dunaway and provided courtesy of US Army)

A CH-47 Chinook helicopter refuels in Jalalabad, Afghanistan. TARDEC supports the *AFI* objective, under which DoD/OUSD AT&L will catalyze commercial industry to produce clean fuels for military aircraft such as this one from secure, domestic resources. (Photo by SSGT Marcus J. Quarterman and provided courtesy of US Army)

THERMAL MANAGEMENT TECHNOLOGY

The DoD's increasing electrical power demand translates to an increased thermal management requirement at the component and vehicle levels. To address this growing capability gap, TARDEC is leading a new FY08 ATO that focuses on advancing and applying power and thermal management technologies to military systems.

The ATO's goal is to develop technology that improves electrical power usage. Specifically, the improvements are aimed at reducing power loss at the component level and increasing the efficiency of waste-heat removal in current and future tactical and combat ground vehicle systems. Power management has been a subject of serious work for the past few years, but recently it has become clear that any work completed in this field immediately impacts heat-rejecting systems. Therefore, to maximize efficiency, this program will be tailored to address both power and thermal management as dependent factors.

Although the Power and Thermal Management program is only scheduled for three years of research, thermal management was identified as an important technology area needing additional investment. Fundamentally, this project is designed to provide working solutions for soldiers. An intelligent power management system with integrated thermal management will reduce the crew burden by automating certain processes and will ultimately result in more available power for soldiers to accomplish their mission.

Modeling and simulation (M&S) can be used to seek out various technologies. Thermal modeling toolsets, such as the Cooling System Evaluation Tool, were developed to increase TARDEC's core capability in thermal M&S. HE thermal demands motivated the development of a carbon foam cold plate for power inverters, and carbon foam radiators were developed for HMMWVs and compared to a baseline radiator. Thermal management has increased in importance with the increase in electrical equipment in crew compartments and also with the recent emphasis on HEVs and the increased use of power electronics. TARDEC's M&S and test and evaluation efforts seek to understand the component- and system-level impacts of advanced heat-rejecting materials and cooling methodologies, with application to power electronics. The overall system will improve electrical stability and efficiency and increase heat rejection by linking power and thermal management strategies into an integrated onboard architecture.

There are several ongoing programs building on past efforts. Some of these efforts include the optimization of power sources and loads using artificial intelligence, a CRADA that incorporates thermal data into the existing models, and several enhancements to the Electronic Power Architecture Systems Integration Laboratory to accommodate high-voltage components, prepare for thermal testing of power electronic devices and verification of thermal component modeling.

This new ATO program will focus on researching methods to increase component life, reduce and recover waste heat energy, extend silent missions, increase battery reserve and increase operating temperatures of solid state electronics. Several of the planned future programs will be in collaboration with universities, industry and government research facilities. Some of these programs include:

- The enhancement of a power management optimization cost function that incorporates thermal data with research into the miniaturization of power control units.
- Development of carbon foam radiators for FCS.
- Integration of phase change technology and carbon foam.
- Research on a high-efficiency waste heat recovery system using advanced materials such as depleted uranium.
- Development of nano-fluids as a coolant for prime-power and/or electrical systems.
- A power and thermal management prototype/demonstration in collaboration with the Non-primary Power Systems ATO program to integrate an APU as a power source.

Based on feedback from a Power and Energy Symposium hosted by TARDEC in 2008, power and thermal management is an area of growing interest to both government and industry. This ATO program will advance hardware and software components and systems, resulting in the Army's vision of an integrated power and thermal management architecture.

SYNTHETIC FUELS

As previously noted, the US is looking for ways to reduce dependence on foreign energy sources. High fuel costs are hitting the military as hard as consumers, so efforts such as those initiated in 2004 by the Office of the Secretary of Defense's *Assured Fuels Initiative* (AFI) to seek secure, domestically-sourced clean energy alternatives continue today.

TARDEC embraced the international effort for research and development (R&D) of non-petroleum-derived kerosene (synthetic jet fuel) through its efforts under the *AFI*. The *AFI* objective is that the DoD/Office of the Under Secretary of Defense for Acquisition, Technology and Logistics (OUSD (AT&L)) catalyzes commercial industry to produce clean fuels for the military from secure, domestic resources. DoD's role as the catalyst in attaining this vision is threefold:

- Engage in the development of alternative fuel specifications.
- Certify, qualify and demonstrate the use of alternative fuels in DoD tactical vehicles, aircraft and ships.
- Implement the use of alternative fuels in DoD tactical vehicles, aircraft and ships operating throughout the continental US.

TARDEC has been a key participant in the *AFI*, beginning in 2003 with laboratory evaluations of synthetic fuel, namely Fischer-Tropsch (FT) synthetic kerosene. The coordination of DoD synthetic fuel specification development with that of the commercial aviation industry was spearheaded by TARDEC's NAC in May 2003 and continued into 2007. This coordination was established through the Aviation Committee of the Coordinating Research Council (CRC-AC), which includes representation from the airframe and jet engine original equipment manufacturers (OEMs), jet fuel producers and government agencies such as the Military Services, Defense Energy Support Center, NASA and Federal Aviation Administration.

Although CRC-AC is not responsible for regulation, hardware or fuel development, or setting standards, its efforts to direct engineering and environmental studies indirectly influence these areas. ASTM International, which maintains the fuel specification used by US commercial aviation, looks to CRC-AC to provide guidance regarding non-petroleum-derived kerosene and its potential suitability for use by US commercial aviation.

The effort under the *AFI* carries forth today, underpinned by the Air Force objective as stated by former Secretary of the Air Force Michael W. Wynne in July 2007:

"The Air Force is committed to completing its testing and certification of our aircraft fleet for alternative fuels by 2011. Working with industry, we can accomplish this goal. Once accomplished, we look forward to buying domestically produced synthetic fuel at competitive market prices from manufacturing facilities that engage in effective carbon dioxide capture and reuse."

In January 2008, CRC-AC published a report, *Development of the Protocol for Acceptance of Synthetic Fuels Under Commercial Specification*. This protocol is intended to establish that once a synthetic fuel (including blends of synthetic and petroleum-derived fuel) is accepted as suitable for use by the aircraft engine OEM and written into fuel specifications and/or service bulletins, the fuel will automatically be an approved fuel under the fuel specification for US commercial aviation (ASTM D1655-08, *Standard Specification for Aviation Turbine Fuels*). This is a significant *AFI*-supporting milestone, because having an agreed on and documented protocol for acceptance of synthetic jet fuel is a critical step in establishing a market for it.

Between the commencement of TARDEC evaluations of synthetic kerosene and coordination of fuel specification development through CRC-AC, NAC represented TARDEC efforts targeting *AFI* goals in other forums with international ties. In 2003, 2005 and 2007, NAC participated in the biennial conference of the International Association for the Stability, Handling and Use of Liquid Fuels, which promotes research and experimentation on scientific and operational factors affecting the stability, handling and use of fuels from manufacture to end use and disposal. The most recent conference in October 2007 focused on alternative fuels. More than 50 speakers presented highlights from their R&D areas, including FT synthetic fuels.

NAC presented two posters, one of which highlighted TARDEC evaluations of FT synthetic kerosene. The second poster highlighted results of a study examining the potential to use up to 50%, by volume, of FT synthetic kerosene in blends with the jet propellant 8 (JP-8), a commercial jet fuel (Jet A-1) with military-approved additives that is typically used at the five US Army installations included in the study.

NAC also participated in the 2005 Aviation Fuel Forum of the International Air Transport Association (IATA), an organization comprised of 270 member airlines representing 94% of scheduled international air traffic and with a mission to lead, represent and serve the airline industry. IATA's Aviation Fuel Working Group (AFWG) formulates the technical basis for an international specification guide for aviation turbine fuels that IATA develops and maintains. In May 2005, NAC introduced the AFWG to *AFI*'s vision and goals. At that time, the AFWG had already been considering use of synthetic jet fuels for commercial aviation, primarily based on the successful use of FT kerosene in blends with Jet A-1 at Johannesburg International Airport in Johannesburg, Gauteng, South Africa. Since JP-8 is derived from Jet A-1, it is essential that both the US military and the commercial aviation industry nationally and worldwide are aligned in requirements for synthetically produced Jet A-1.

Through its involvement with forward-thinking projects such as the *AFI*, TARDEC is, once again, asserting its position at the forefront of emerging alternative energy R&D and implementation.

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[1] Bollinger, Jr., P. P., *Army Energy Security Task Force Briefing to ADC Annual Conference*, April 2008.

TARDEC is the nation's laboratory for advanced military ground systems and automotive technology. A leading technology integrator for the US Army Materiel Command's Research Development and Engineering Command (RDECOM), TARDEC is headquartered at the Detroit Arsenal in Warren, MI, located in the heart of the world's automotive capitol. TARDEC is a major element of RDECOM and a partner in the TACOM Life Cycle Management Command. As a full life-cycle engineering support provider-of-first-choice for all DoD ground combat and combat support weapons and vehicle systems, TARDEC develops and integrates the right technology solutions to improve Current Force effectiveness and provide superior capabilities for the Future Force. TARDEC's technical staff leads research in ground vehicle survivability; mobility/power and energy; robotics and intelligent systems; maneuver support and sustainment; and vehicle electronics and architecture. TARDEC develops and maintains ground vehicles for all US Armed Forces and numerous federal agencies.

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